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WAVES IN SOIL DURING A SURFACE BLAST
AND THEIR INTERACTION WITH OBSTACLES

by

G. M. Lyakhov and R. I. Dubova

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13. ABSTRACT

In an earlier work, several results were given of experimental studies of waves generated in soil by surface explosions, where the charge was placed on the soil surface. In the present paper, the results of experiments are presented which compare the waves generated by underground and surface explosions. The reflection of waves from stationary obstacles is discussed. The experiments were carried out in a disturbed sandy soil (sandy fill). TNT charges were used ranging from 0.2 to 1.6 kg. The wave parameters were recorded, using high frequency tensometers, on an oscillograph. Sensors were placed in the soil along lines perpendicular to the surface and radial lines. [AT6034255]

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

WAVES IN SOIL DURING A SURFACE BLAST AND THEIR INTERACTION WITH OBSTACLES

G. M. Lyakhov and R. I. Dubova

Proposed in [1] were some of the results of experimental investigations of waves in soil during a surface blast when the center of the concentrated explosive charge coincides with the surface of the soil. Given below are the results of the experiments completed during the process of this work. A comparison of the waves was made during camouflet and surface blasts. The reflection of the wave against stationary obstacles was examined.

Conditions for conducting the experiments

The experiments were conducted in a sandy soil with a disturbed structure (fill sand) and the soil skeleton having a volume weight of γ = 1.45-1.50 g/cm^3 and moisture by weight W = 3-6%. The grain-size distribution of the sand: particles with a diameter greater than 0 5 mm comprise 30-40%, diameters of 0.5-0.25 mm – 30-40%, diameters of 0.25-0.1 mm – 15-20% and less than 0.1 mm – 3-8%.

The waves were produced during blasts of concentrated charges of molded TNT with a weight of 0.2; 0.4; 0.8; and 1.6 kg.

The parameters of the waves were recorded with the aid of high-quality strain gage sensors whose readings were taken on a loop oscillograph.

The sensors were placed in the soil under the charge on an axis perpendicular to the surface of the soil, which we will designate as the axis of the blast, and along the radii whose angle between them and the axis is 30, 45 and 60°.

Let us designate R° as the relative distance

$$R^{\circ}=R/\sqrt[3]{C} \quad \mu g^{-1/3}, \qquad (1)$$

where R – distance from the center of the blast, m; C – weight of the explosive charge, kg.

At each given distance from the blast two sensors are placed. The sensing element of on of the sensors was oriented along the normal, and the other one – parallel to the direction of the wave movement. In the first case the radial (normal) $p = p_r(t)$ was recorded, and in the second case – the later $p_\tau = p_\tau(t)$ pressure (t – time).

The measurements were made within the range of relative distances

$$0.33<R^{\circ}<1.5 \quad \mu g^{-1/3}. \qquad (2)$$

In addition, the measurements were made in the surface zone. At each given distance from the blast, three sensors were placed. The sensing element of one of them was set perpendicular to the surface of the soil, the second one facing the axis of the blast, and the third – perpendicular to the first two. The sensors recorded the three component directions which can act as the three faces of the obstacle having the form of a parallelepiped.

During the determination by oscillograms of the build-up pressure time τ, pressure action time θ and the impulse of the wave, the time intervals were calculated at pressure values which comprised no less than 0.05 of the maximum value.

For a comparison of the waves which form during surface and camouflet blasts, experiments with buried charges were conducted in the same soil. The sensors in this case were placed at one depth with the explosive charge, and the normal and lateral pressures were measured.

Investigation of the parameters of the compression waves in the soil

Let us examine the relationship $p = p(t)$, i.e., the profile of the wave during a camouflet and surface blast.

The oscillogram shown in Fig. 1a is a recording of the pressure during a camouflet blast. The weight of the charge $C = 0.2$ kg. The first half-line – is the time marker (period of oscillation $T = 0.002$ s). The third from the time marker – the instant of the blast. The second, fourth and fifth half-lines correspond to the sensors which measured the normal pressure at distances from the site of the blast, $R = 0.47$, 0.31 and 0.63 m. The sixth half-line characterizes the lateral pressure when $R = 0.63$ m.

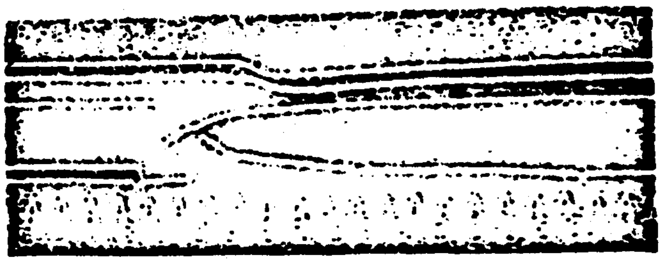

Fig. 1a. Oscillogram of a recording of the pressure during a camouflet blast.

GRAPHIC NOT REPRODUCIBLE

From the oscillogram it is obvious that when $R \leq 0.47$ m or $R^0 \leq 0.8\ \mu g^{-1/3}$ the blast wave has a pressure jump at the front, and at the remaining distances the pressure build up proceeds gradually.

Figure 1b shows an oscillogram recorded during a surface blast with sensors located on the axis under the charge. The weight of

the charge C = 1.6 kg. The first half-line – the time marker, and the third records the instant of the blast. The second and sixth half-lines record the lateral pressure when R = 0.8 m, the fourth and fifth half-lines – the normal pressure when R = 0.8 and 0.4 m.

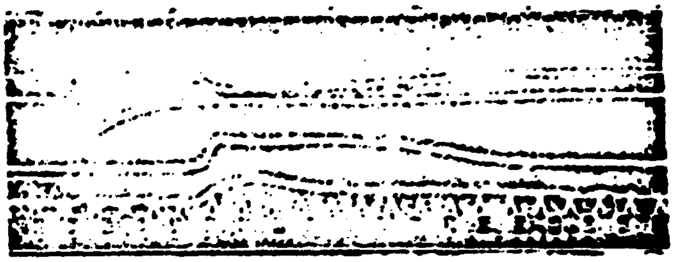

Fig. 1b. Oscillogram of the recording of the pressure during a surface blast.

GRAPHIC NOT REPRODUCIBLE

From the oscillogram it follows that the wave has a pressure jump at the front only when $R \leq 0.4$ m or $R^0 \leq 0.34$ $\mu g^{-1/3}$. In this way the wave ceases to be a shock wave during a surface blast at smaller relative distances than during a camouflet blast, but approximately at the same pressure values which fall within the limits of 4 to 6 kg/cm^2.

Let us designate Θ as the relative time of the pressure action

$$\Theta^0 = \Theta / \sqrt[3]{C} \ \mathrm{s \cdot kg}^{-1/3} \qquad (3)$$

The conducted experiments indicate that Θ^0 increases with an increase in the distance from the placement of the charge both during camouflet and surface blasts.

The relationship of Θ^0 to R^0 in the investigated range of distances in the first approximation can be taken linearly –

$$\Theta^0 = \eta + \upsilon R_0$$

$$\Theta^0 = \sqrt[3]{0{,}3}\,\eta + \upsilon R^0. \qquad (4)$$

The first of the formulae (4) corresponds to the camouflet, and the second – to the surface blast. In the second case the measurements were made on the axis of the blast.

In the case of the investigated soil

$$\tau_1 = 16\cdot 10^{-3}\ \mathrm{s\cdot kg^{-1/3}},\quad \nu = 24\cdot 10^{-3}\ \mathrm{s\cdot m^{-1}}.$$

During a surface blast Θ^0 has smaller values than during a camouflet blast.

Figure 2 shows the dependence of the propagation rates of the wave front D and the maximum pressure D_m during a camouflet blast, on R^0.

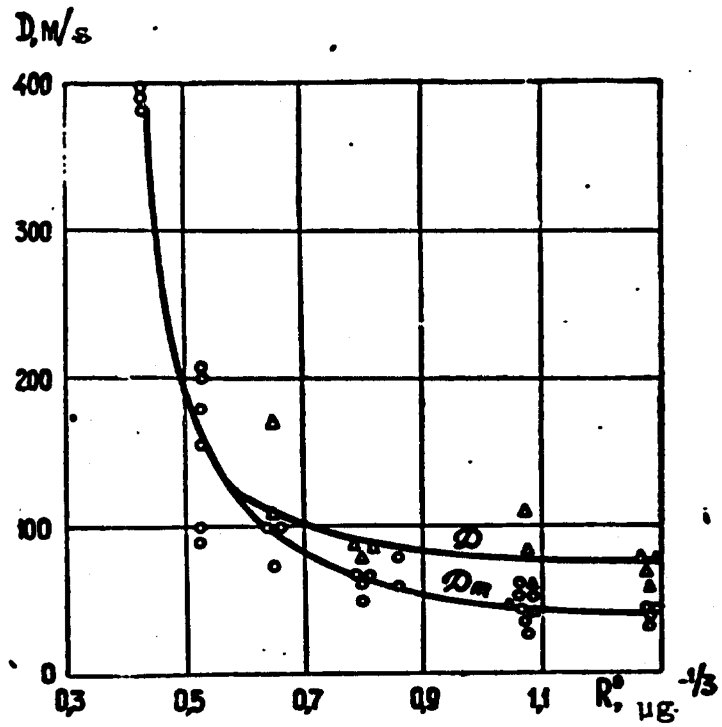

Fig. 2. The dependence of the propagation rate of the wave front (circles) and maximum pressure (triangles) on the relative distance during a camouflet blast.

With small R^0 the values of D and D_m coincide since the wave is a shock wave and the build-up time of the pressure is equal to zero.

Within this range a drastic reduction in D takes place with an increase in R^0. At larger distances D and D_m are different, and

the drop in both rates with an increase in R^0 is insignificant.

Figure 3 gives the dependence of D and D_m on R^0, which corresponds to the surface blast and to the measurement made on the axis under the charge.

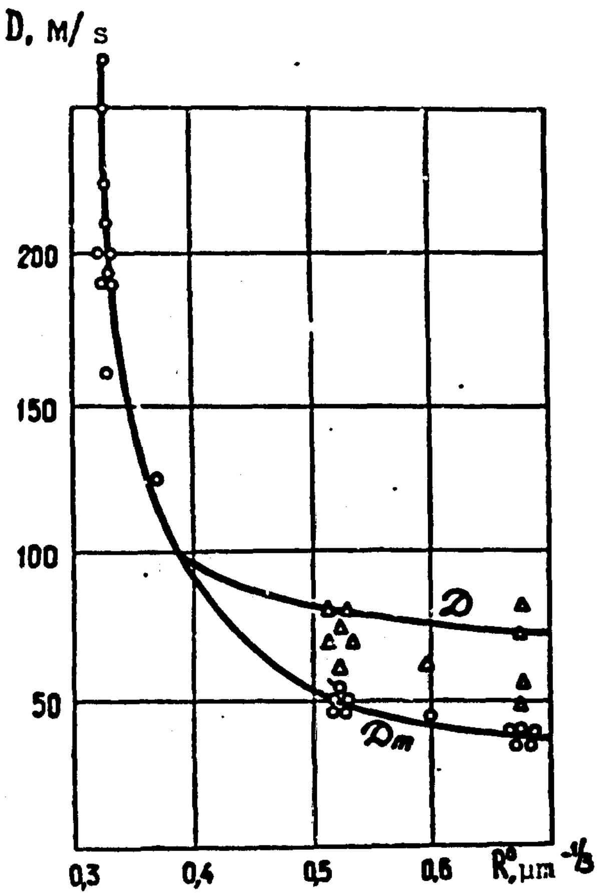

Fig. 3. The dependence of the propagation rate of the wave front and the maximum pressure on the relative distance during a surface blast.

The disintegration of the pressure jump in the case of the surface blast occurs with smaller R^0 than during a camouflet blast, but approximately at these same values of pressure.

The values of D and D_m at a sufficient distance from the site of the blast in both cases are correspondingly equal.

Let us examine the dependence of the maximum values p_r and p_τ of the normal and lateral pressures on the distance R^0 during camouflet blasts which are shown in Fig. 4. Curve 1 corresponds to a normal pressure, and curve 2 – to a lateral pressure. Curve 3 was taken from [2]. It indicates the normal pressure in a sandy soil with an undisturbed structure having γ = 1.52-1.60 g/cm^3 and a moisture content W = 8-10%.

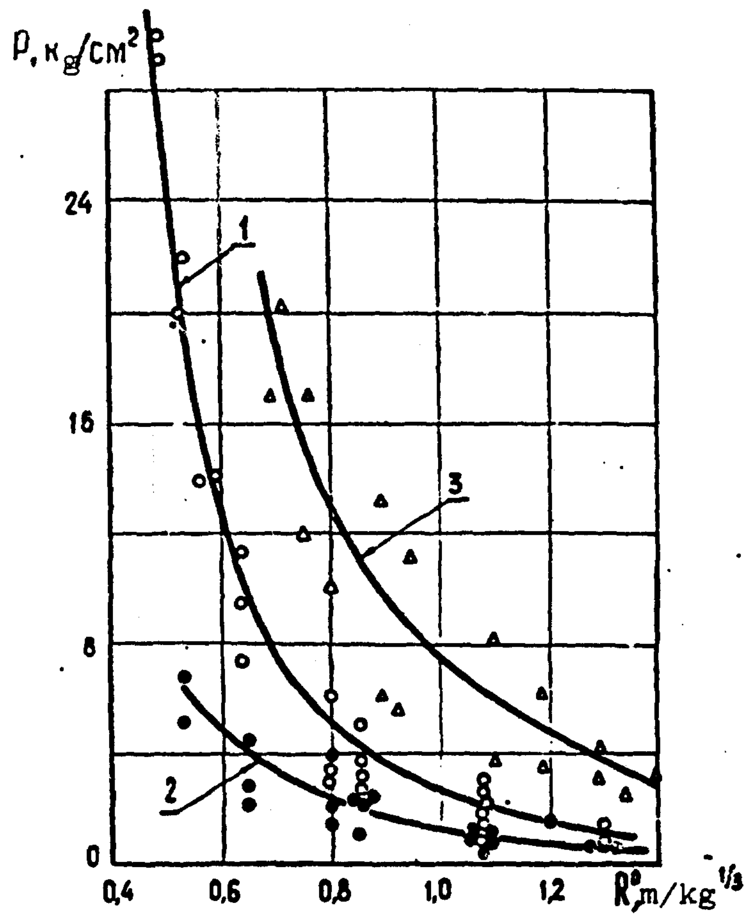

Fig. 4. The dependence of the maximum values of the normal and lateral pressure on the relative distance during a camouflet blast.

From the graphs presented in Fig. 4, it follows that in a soil with a disturbed structure, the pressure drop with distance R^0 occurs more intensively than in a soil in the natural state.

The lateral pressure p_τ within the entire investigated range of distances is associated with p_r by the relationship

$$p_\tau = k_\tau p_r \qquad (5)$$

The coefficient of lateral pressure k_τ lies within the limits of 0.4 to 0.5.

Thus, the normal and lateral pressures are substantially different, but similar in the fact that they occur in solids.

In [2] it was pointed out that the dependence of the maximum value of normal pressure p_r on R^0 in soils during a camouflet explosion can be represented in a form which satisfies the principle of similitude, –

$$p_r = k_1\left(\frac{\sqrt[3]{C}}{R}\right)^{\mu_1}. \qquad (6)$$

here, p_r – kg/cm^2, C – kg, R – m.

The values k_1 and μ_1 depend on the properties of the soil.

If γ = 1.52-1.60 g/cm^3 and W = 8-10%, then k_1 = 7.5 and μ_1 = 3. From the graphs in Fig. 4 it follows that the equation (6) also corresponds to the pressure P_r in the investigated soil; in this case k_1 = 2.8 and μ_1 = 3.3.

Figure 5 shows the relationship of the normal pressure (curves 1 and 3) and lateral pressure (curves 2 and 4) on R^0, produced during a surface blast and the location of the sensors on the axis (curve 1 and 2) and at angle ϕ, on the axis equal to 30° (curves 3 and 4).

From a comparison of the graphs it follows that with an increase in angle ϕ the normal and lateral pressures are lowered.

The dependence of the maximum value of normal pressure p_r on R^0, which corresponds to a surface blast and to the measurements

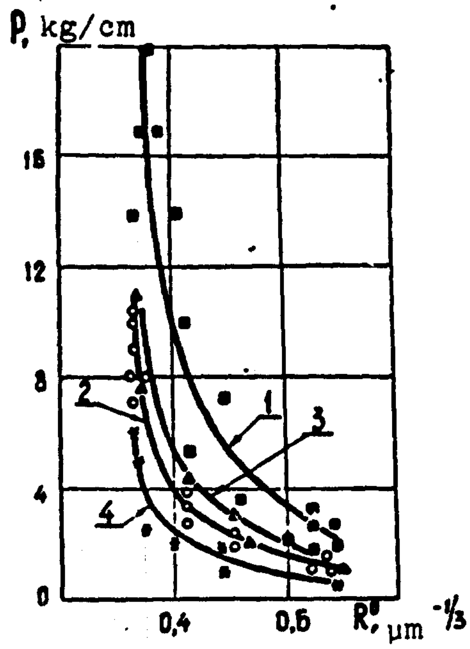

Fig. 5. The dependence of the normal and lateral pressures on the relative distance during a surface blast.

on the axis under the charge (graph 1 in Fig. 5), can be presented in the form

$$p_r = k_1\left(\frac{\sqrt[3]{0,3C}}{R}\right)^{\mu_1}, \qquad (7)$$

where just as during a camouflet blast, $k_1 = 2.8$, and $\mu_1 = 3.3$.

The maximum value of the lateral pressure in this case is determined by the formula

$$p_\tau = k_\tau p_r, \quad (0,4 < k_\tau < 0,5). \qquad (8)$$

The results of measuring the pressure along the radii wiich consist of angle ϕ with the axis of the blast, indicate that when $\phi \leq 45°$ in the first approximation one can take

$$p_r(\varphi) = p_r(0)\cos\varphi,$$
$$p_\tau(\varphi) = k_\tau p_r(\varphi). \qquad (9)$$

With an increase in ϕ within this range, the normal and lateral pressures are reduced. In the surface zone an opposing relationship occurs – with proximity to the surface the pressure increases.

From the results of the experiments it follows that the blast wave impulse I in the soil during a surface has smaller values than during a camouflet blast. Dependence I on the distance R and the weight of the charge C can be presented in the form proposed in [2], –

$$I=k_2\sqrt[3]{C}\left(\frac{\sqrt[3]{C}}{R}\right)^{\mu_2}; \quad I=k_2\sqrt[3]{0{,}3C}\left(\frac{\sqrt[3]{0{,}3C}}{R}\right)^{\mu_2}. \qquad (10)$$

Here, I – $kg \cdot s \cdot cm^{-2}$.

The first of the formulae (10) corresponds to a camouflet blast, and the second – to a surface blast. In the second case the measurements were made on the axis of the blast with sensors whose sensing elements faced the blast.

In the case of the investigated soil in the formulae (10)

$$k_2=0{,}32, \qquad \mu_2=1{,}5.$$

The results of measuring the impulse along the radii originating from the center, and comprising angle ϕ with the axis of the blast, indicate that with an increase in ϕ the impulse is reduced.

Within the range of change $0 \leq \phi \leq 45°$ in the first approximation one can assume that

$$I(\varphi)=I(O)\cos\varphi. \qquad (11)$$

where I(0) corresponds to the measurement on the axis of the blast determined by the second of the formulae (10).

With an increase in angle ϕ in the surface zone the impulse just as the pressure, increases.

The above examined value of Θ does not altogether accurately characterize the duration of the blast wave action which should be taken into account in the calculation of the loads on the obstacles, since Θ is included in the interval of time during which p is small. In addition, Θ is determined as a result of the insignificance of p in the back part of the wave having large errors. Therefore, it is expedient to introduce an effective time action Θ, by determining it from the condition

$$I^{\circ}=\frac{p_{r}\Theta^{*}}{2}, \qquad \Theta^{*}=\frac{2I^{\circ}}{p}. \tag{12}$$

Or by calculating (6), (7) and (10) for the camouflet blast, we will obtain

$$\Theta^{*}=\frac{2k_{2}}{k_{1}}\left(\frac{\sqrt[3]{C}}{R}\right)^{\mu_{2}-\mu_{1}} \tag{13}$$

and for the surface blast the ϕ = 0 –

$$\Theta^{*}=\frac{2k_{2}}{k_{1}}\left(\frac{\sqrt[3]{0{,}3C}}{R}\right)^{\mu_{2}-\mu_{1}}. \tag{14}$$

From the experiments it follows that the formulae for the determination of the parameters of the wave p, Θ, I, corresponding to the surface blast and the axis of the blast, in a direction vertically downward (ϕ = 0), can be obtained from formulae for a camouflet blast if the weight of the explosive charge in place of C is taken to be equal to 0.3 C.

Thus, during a blast of an explosive charge with a weight C at the boundary of the soil-air media, the wave in the soil, going

downward from the center of the blast, is equivalent to a wave from a camouflet blast produced by a charge with a weight $\lambda_1 C$. For the investigated soil, $\lambda_1 = 0.3$.

M. A. Sadovskiy [3] based on experimental investigations proposed a formula for determining the maximum pressure at the front of an air shock wave, in the form

$$p=0,76\frac{\sqrt[3]{C}}{R}+2,55\frac{\sqrt[3]{C^2}}{R^2}+6,5\frac{C}{R^3}. \qquad (15)$$

The energy liberated during the blast at the boundary of the air with the two-dimensional obstacle made of a non-compressible material with infinite mass, as is known, fully enters the process occurring in the air. The parameters of the air wave in space, in this case, can be obtained from formula (15), by taking the weight of the explosive charge as equal to 2C.

From our experiments it follows that during the blast of a charge at the soil-air boundary, it is necessary to regard the soil as a non-compressible, boundless medium. The parameters of the air shock wave therefore can be calculated according to the formula of M. A. Sadovskiy for a boundless medium; however, the weight of the explosive charge should be taken as equal to $\lambda_2 C$. For the investigated soil, $\lambda_2 = 1.4$.

From an analysis of the experiments of K. Lempson [4] conducted on various sandy and clayey soils of the USA, it follows that during a surface blast, $\lambda_1 \geq 0.2$.

Thus, experiments on various unsaturated soils give values close to λ_1. During the experimentation in water saturated soils whose compressibility have smaller values, the value of λ_1 will be somewhat smaller, and the value of λ_2 — larger.

Figure 6 shows graphs of the dependence of the pressure on the distance in the surface area corresponding to the surface blast using a charge with a weight C = 1.6 kg.

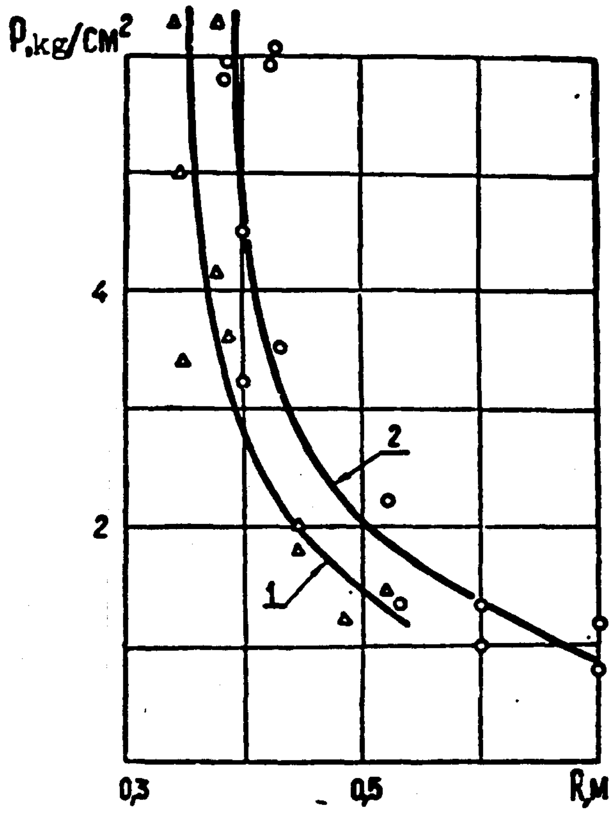

Fig. 6. The dependence of the pressure on the distance in the surface area, corresponding to a surface blast of a charge.

Curves 1 and 2 correspond to the depth of the sensors, equal to 20 and 10 cm. The experiments indicate that with an increase in the depth the value of the pressure is reduced in all the investigated variations of the orientation of the sensors.

The results of the conducted investigations make it possible to propose that a field of stresses is created in the soil as a result of the superimposition of two waves. One is propagated from the center of the blast through the soil (primary wave). The second is caused by the air shock wave which, in passing over the surface of the soil, creates a secondary compression wave in it.

The maxima of pressures of the primary and secondary waves do not coincide with time. Based on the distance from the site of the blast, the pressure created by the primary wave, diminishes faster than the pressure of the secondary wave. Therefore at the greater distances from the site of the blast, only the effect of the latter can be taken into account. The velocity distribution of the air shock wave exceeds the velocity of the wave in the soil. Therefore, the slope angle of the secondary wave to the surface of the soil is small. In the first approximation it can be assumed that the secondary wave moves vertically downward.

In the area under the charge within the limits of angle $\phi \leq 45°$, one can consider that the field of stresses is governed by the action of only one wave passing from the center of the blast, since the secondary wave rapidly expends itself with depth, and its effect in this area hardly needs mention.

Investigation of the reflection of a wave against an obstacle

This involves a wave produced during a surface blast, reflected by an obstacle which is located in the soil. The obstacle consists of a steel plate anchored in a concrete footing. The size of the obstacle by design is 4×4 m^2, with a height of 1 m. During the blasts as measurements indicated, the obstacle did not shift. The soil beneath it had those same physico-mechanical characteristics as in the experiments for the investigation of the propagation of the waves.

The charge was placed over the center of the plate on the surface of the soil. Owing to the large size of the obstacle the flow-around of the wave did not have an effect in the central area.

From the results of the experiments it follows that the presence of a plate in the soil, i.e., an underlying layer with a substantially larger acoustical resistance than the soil, the

incident wave is reflected in the form of a compression wave. In this case the field of stresses in the soil under the charge is the result of the superimposition of two waves: the incident and reflected waves. In the surface area around the explosive charge a field of stresses is produced as the result of the interaction of the three waves: that going out from the center of the blast, that reflected from the underlying layer, and the underground wave, produced by the air shock wave passing over the surface of the soil.

The dependence of the stress on the time appears to be extremely complex, since the waves pass through the examined point in the soil at a different time, along different directions, have different pressure values and time effects. In the first approximation the field of stresses can be determined as the result of the geometric complexity of the fields creating each of the waves.

The experiments indicate that with a maximum pressure in the incident wave p_r, falling with the range of 1.5 to 2.0 kg/cm^2, the maximum load acting on the obstacle in the investigated soil, consists of 4.6 to 6.0 kg/cm^2. When p_r equal to 5-6 kg/cm^2 the load on the obstacle reaches 14-17 kg/cm^2. Thus, the reflection coefficient χ is approximately equal to 3. Consequently, the regularities of the reflection of the waves in sandy soil with a disturbed structure differ somewhat from the regularities linearly characteristic of an elastic medium when $\chi = 2$.

Figure 7 shows graphs of the dependence of the pressure in an incident wave produced by a surface blast with a charge C = 1.6 kg, and in a wave reflected from an obstacle.

The results of numerous experiments [1, 2] indicate that in various sandy and clayey unsaturated soils of a natural composition and with a disturbed structure, the coefficient of lateral pressure k_τ has different values: from 0.25 to 0.6. In each soil within

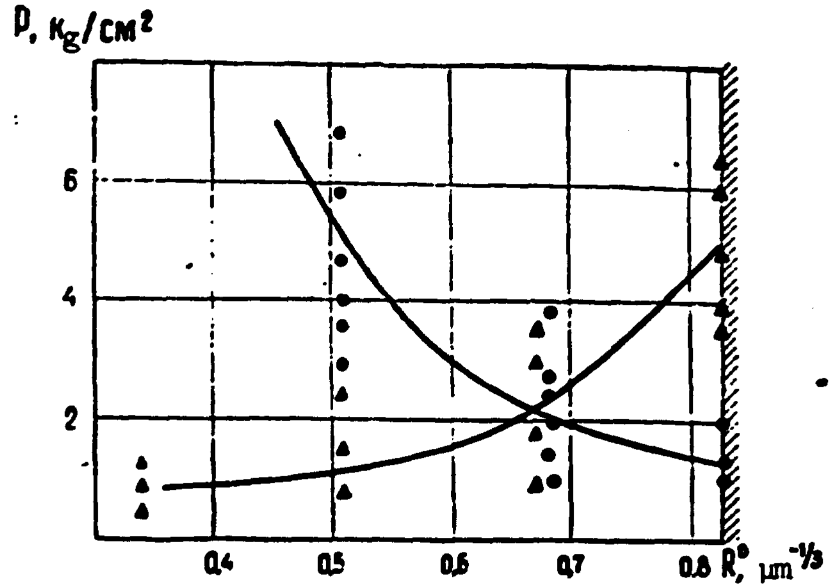

Fig. 7. The dependence of the pressure in an incident wave produced by a surface blast using a charge, and in a wave reflected from an obstacle.

the investigated range of pressures: from 2-3 to 40-50 kg/cm^2 – during surface and camouflet blasts k_τ changes slightly and in the first approximation can be taken as a constant.

Let us find, based on constancy k_τ, the condition of plasticity of unsaturated soils.

S. S. Grigoryan [5] proposed a model of the soil according to which the intensity of the shear stresses during the plastic state of the medium determined by the second interval of the deviator of the tensor of stresses, is a certain function of the average stress (the Mises-Schleicher condition of plasticity [6]).

$$I^2 = f(N).$$

The form of this function is found from the experiment.

In the case of wave movement with a planar or spherical front we will have

$$3N = p_r + 2p_\tau; \qquad 3I_2 = -(p_r - p_\tau)^2.$$

From the condition of constancy k_r, let us find the function of plasticity in the form

$$f(N)=-\frac{1}{3}(p_r-p_\tau)^2=-3\left[\frac{(1-k_\tau)N}{1+2k_\tau}\right]^2.$$

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E053	AF/INAKA	1
E017	AF/RDCC - AFSC	1
E018	AF/RDGC - SAMSO	1
	ARL/CA	2
E404	AEDC	1
E408	AFWL	1
E410	ADTC	1
E413	ESD	2
	AFCRL (CRTE) (1)	
E427	RADC	1
E429	SAMSO	1
	FTD	
	LNA	1
	CCN	1
	NIA/PHS	2
	NIIR	10
	NIT	1
	PDT/PHE	15
	PDYA	1
	PDTN/Ballard	1
	PDTR	1

Organization		Nr. Cys.
DISTRIBUTION DIRECT TO RECIPIENT		
	DDC	12
A205	DMATC	1
A210	DMAAC/PDA	2
B344	DIA/DS-4C	5
C043	SURG GEN	1
C509	ABERDEEN R & D CTR	1
C513	PICATINNY ARSENAL	1
C523	HARRY DIAMOND LAB	1
C535	AVIATION SYS COMD	1
C557	USAIIC	1
C591	FSTC	7
C619	MIA REDSTONE	1
D008	NAVSTIC	1
D217	NAVWPNSCEN	1
D220	ONR	1
H300	USAICE (USAREUR)	1
P055	CIA/CRS/ADD/SD	5
OTHER GOVERNMENT AGENCIES		
	AEC (Wash)	2
	FAA	1
	NASA (ATSS-T)	1